

THE PULSATING WHITE DWARF L 19-2

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Abstract. A progress report on recent observational work undertaken on the pulsating white dwarf L 19-2 is presented. This object was observed during the 1995 multi-site WET campaign, XCOV12. In addition, the star also has been observed from a single-site (Mt. John) in 1994–1997. The high-speed photometric data-base for this object now spans 20 years. The prospects for detecting a period change as a result of evolutionary cooling effects are examined.

Key words: stars: white dwarfs, oscillations, individual: L 19-2

1. INTRODUCTION

The white dwarf L 19-2 (MY Aps, WD 1425-811) is a member of the coolest group of white dwarf pulsators, the DAV class. These hydrogen-atmosphere compact objects have $T_{\text{eff}} \approx 12\,000$ K and pulsate in nonradial g -modes with periods between about 100 s and 1000 s. As a group, the DAVs roughly divide into the cooler atmosphere larger amplitude pulsators and the hotter atmosphere smaller amplitude pulsators, with only a few modes evident in the photometric data. L 19-2 is one of the latter objects, and has a relatively simple period structure in the range 113 s to 350 s, with a relatively dominant pulsation mode at 192.6 s.

Theoretical investigations of the g -mode pulsation properties of the compact objects (Bradley & Winget 1991, Brassard et al. 1992) indicate that the number of available pulsation modes is large. While the hotter objects (DOVs and DBVs) largely exhibit an extensive range of modes (e.g. Winget et al. 1991, 1994) the cooler DAVs invariably reveal only a few of those possible. Whether these other

modes are simply not excited, or they result in photometric variations that are too low to be detected by the current instrumentation suite, the selection mechanism at work has not been identified as yet.

In the past decade, substantial progress has been made in investigating the interior properties of the compact stars using the photometrically-detected pulsation spectrum and the tools of asteroseismology (e.g. Brown & Gilliland 1994). Probing white dwarf interiors using these tools has been most effective when the target yields a large number of excited modes. As a direct result of their parsimonious approach to mode excitation, the cooler DAVs have been recalcitrant subjects in these endeavors. Nevertheless, some progress has been made by some detailed investigations (Bradley 1996, Bradley 1998) and by viewing all the known DAV stars as sample members of a distinct population group (Clemens 1995).

The very sparseness of the hot DAV pulsation mode spectrum leads to one distinct advantage: the investigation of a possible period change of one or more modes becomes *relatively* less difficult. By monitoring the period of an isolated pulsation mode over an extended time base, it is theoretically possible to detect the very small period changes that are anticipated from the effects of evolutionary cooling of the white dwarf. This is not to say that the task of actually measuring the small period changes is straightforward. It most certainly is not. Many years of high quality high-speed photometry are required.

Among the cool DAV white dwarfs, L 19-2 is well-suited to this type of investigation. Commencing in 1994 a photometric campaign on this object was initiated using the telescope facilities at Mt. John University Observatory, and a multi-site campaign was carried out in 1995. The aim was to extend previous work on this object that ceased in the mid eighties.

2. THE XCOV12 OBSERVING RUN

Even though the available single-site photometric data on L 19-2 (O'Donoghue & Warner 1982, 1987) indicated that its period structure was relatively simple, a coordinated Whole Earth Telescope (WET, Nather et al. 1990) campaign (XCOV12) was undertaken on this object in 1995 in order to unambiguously identify all the pulsation modes, including the previously detected fine structure split. This would enable (a) a more definitive asteroseismological investigation to proceed, and (b) a period stability analysis to be undertaken

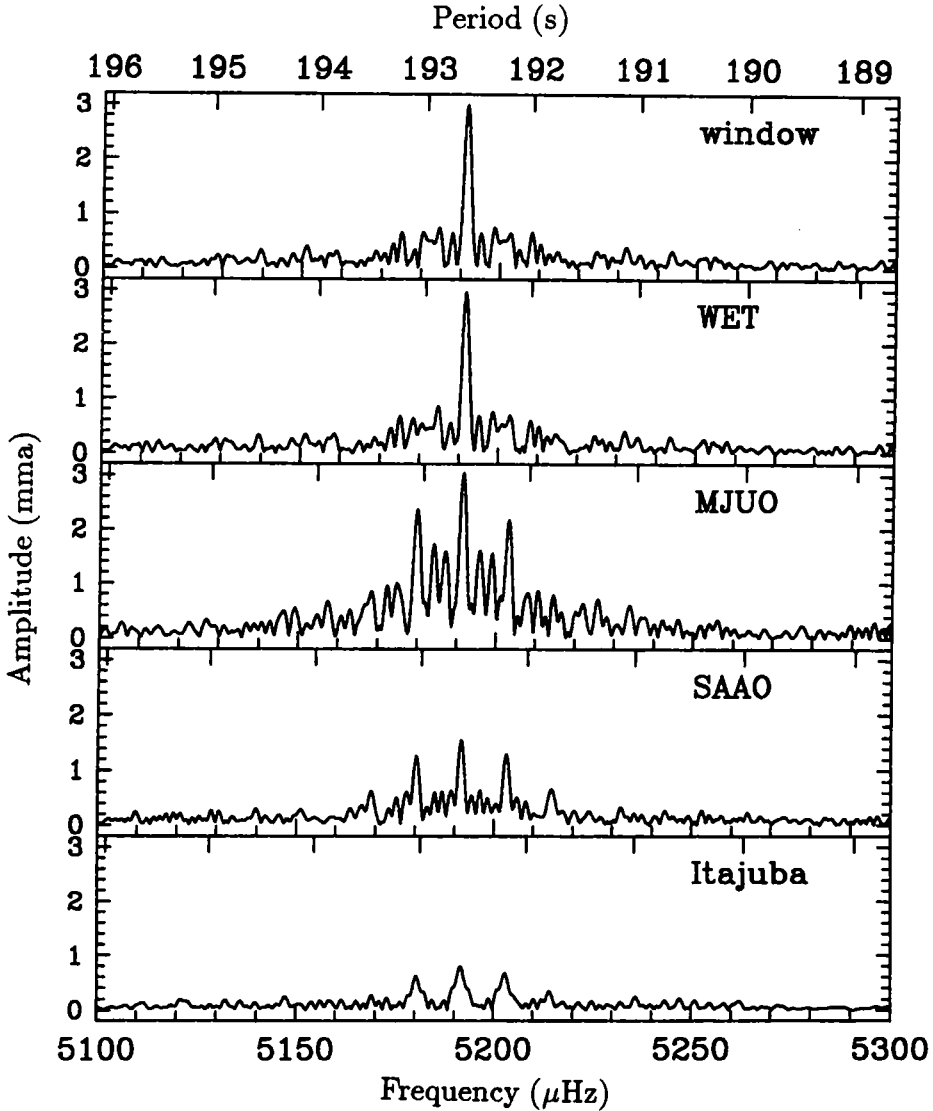


Fig. 1. Amplitude DFTs in the vicinity of the 192 s principal pulsation mode of L 19-2 obtained during the 1995 WET run (XCOV12). The various plots show the DFT of the combined multi-site data, the spectral window for the multi-site data and the DFTs for the individual single-site data (which are significantly affected by the one-day frequency aliases). The light curves used for this analysis were the preliminary ones produced “on-line” during the WET run. The vertical scale is millimodulation amplitude units (mma), wherein 10 mma corresponds to a 1% amplitude modulation.

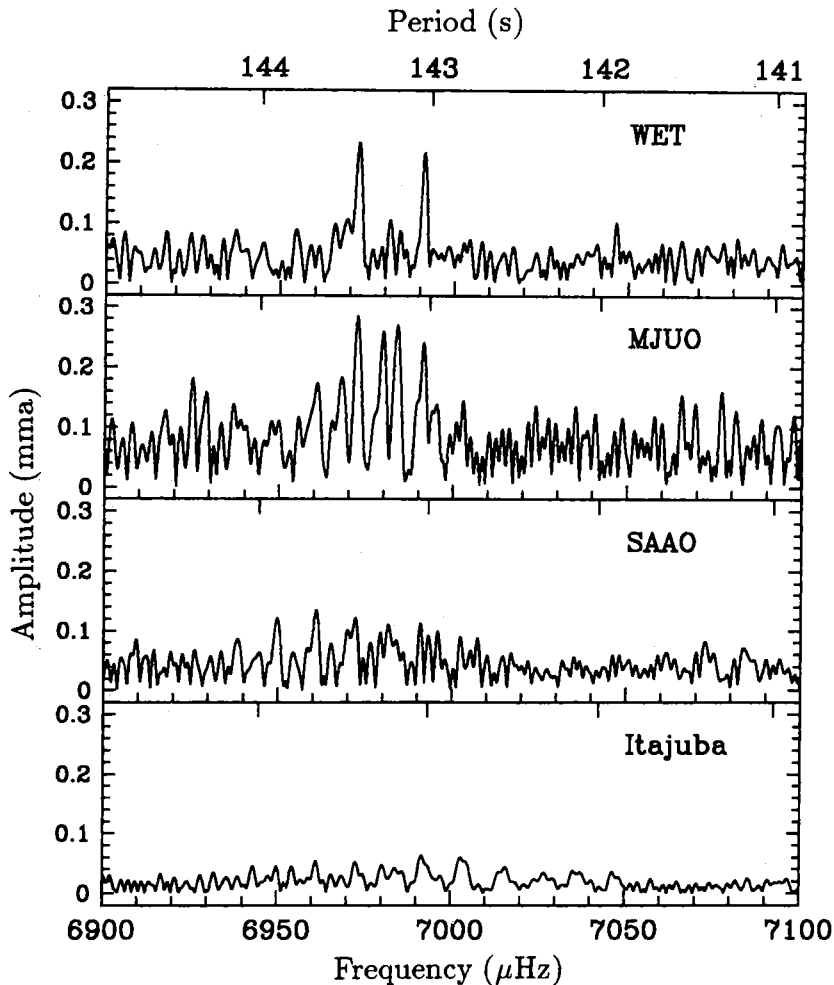


Fig. 2. Amplitude DFTs depicting the two pulsation modes of L 19-2 detected with periods near 143 s during XCOV12. The pulsation amplitudes are readily identifiable in the combined WET data set, but not in the single-site data (except, perhaps for MJUO).

using all available photometric data, which when combined with the earlier data covered a 20 year time base.

The extreme southern declination of L 19-2 meant that only three southern observatories could obtain – weather permitting – essentially continuous coverage. Over a nine day period, Mt. John (New Zealand), SAAO (South Africa) and Itajuba (Brazil) achieved

a duty cycle of nearly 60% (Sullivan 1995). Fig. 1 shows a spectral window function (i.e. a transformed noise-free sinusoid sampled at the same times as the data points) for the whole WET run. The quality of the multi-site data is directly evident in the shape of the window function. It is also made clear by comparing the amplitude DFTs of the WET data with those calculated from the individual single-site data. This information is plotted in the other panels of Fig. 1 for the frequency region in the vicinity of the 192.6 s pulsation mode. The light curves used in this analysis were those produced at the XCOV12 WET headquarters in Ames, Iowa during the run.

Fig. 2 shows amplitude DFT spectra of the periodic structure of the data between 6900 and 7100 μHz . Two pulsation modes are clearly evident in the combined WET data, but (except for the MJUO data) not in the single-site photometry. A glance at the extensive analysis of the earlier single-site data undertaken by O'Donoghue and Warner (1982), will demonstrate how difficult it was to see this low-level pulsation even then.

A comprehensive analysis of the WET data set and additional single-site Mt. John data is in progress and will be published in due course under the full WET collaboration authorship.

3. PERIOD CHANGES IN THE PULSATING WHITE DWARFS

The pulsation modes of the white dwarfs are remarkably stable. This is not so surprising when one realizes that they evolve slowly and at essentially a constant radius. The equilibrium established between the intense self gravity and the degenerate electron core is virtually unaffected by the slow evolutionary cooling of the nondegenerate nuclei component of the structure. Along with the DAV objects, the hotter ($T_{\text{eff}} \approx 25\,000\text{ K}$) helium-atmosphere pulsating white dwarfs (DBVs) are expected to exhibit extremely stable pulsation modes. Even the very hot ($T_{\text{eff}} \approx 10^5\text{ K}$) pre-white dwarf objects (DOVs), where contraction effects are not negligible, are expected to possess relatively stable pulsation periods.

In spite of the fact that the clock mechanisms are intrinsically different (pulsation vs rotation), and there is some disparity in the ease of isolation of a stable frequency, it is interesting to compare the precision white dwarf clocks with that most stable of astronomical clock: the pulsar. Fig. 3 contrasts white dwarf pulsation period stabilities with those of a selection of pulsars: period derivatives ($d\Pi/dt = \dot{\Pi}$) versus period (Π) for both classes of object are plotted

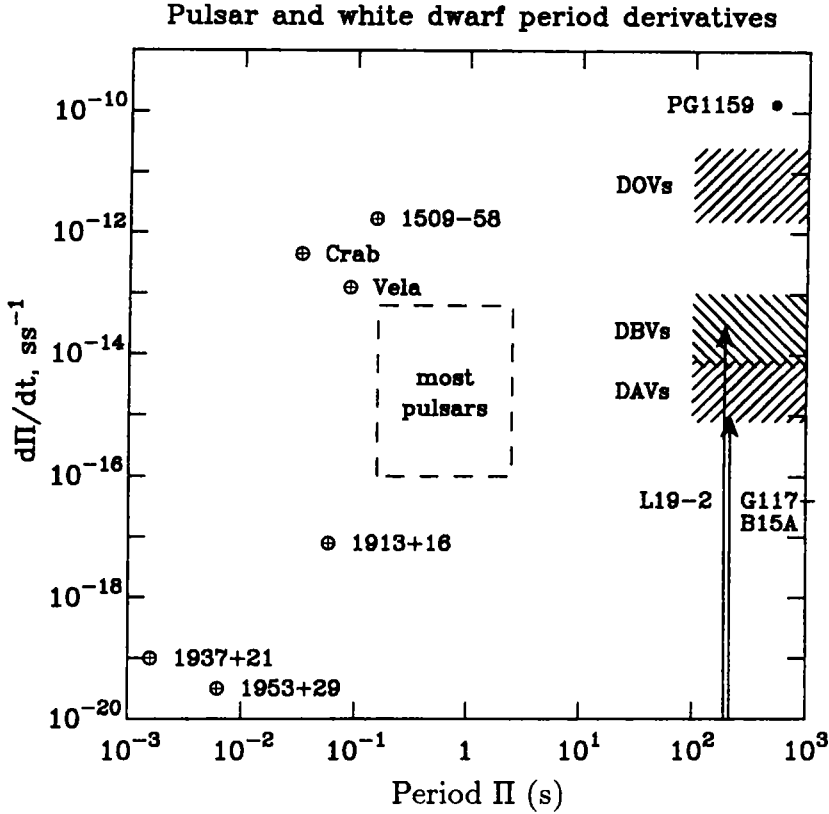


Fig. 3. A comparison of the period stabilities of the pulsating white dwarf and pre-white dwarf stars with a number of pulsars, plotted in the form of period derivative versus period. The cross-hatched regions indicate the theoretically expected period derivatives for the three classes of variable white dwarfs. The white dwarf contribution to the observational data set includes only one definite period increase (PG 1159-035) and two upper limits. The pulsar data were obtained from Taylor and Stinebring (1986) and include the two optically detected pulsars (Crab and Vela), the important general relativistic laboratory (1913+16) and the so-called millisecond pulsar (1937+21).

on the same graph. The pulsar data were obtained from Taylor and Stinebring (1986), and include the two optically detected pulsars (the Crab and Vela) and the intriguing pulsar (1913+16) that acts as the valuable laboratory for tests of general relativity.

The cross-hatched regions in Fig. 3 indicate the range of theoretically expected period derivatives for the three classes of white dwarfs

(DAV, DBV and DOV), obtained from detailed numerical models of the objects (Bradley et al. 1992, 1993; Bradley 1996; Kawaler et al. 1985, 1986; Kawaler & Bradley 1994). Depending on the details of the model such as total mass and core composition, there is variation in $\dot{\Pi}$ by about an order of magnitude for each class, but all appropriate model values are approximately in the range $\dot{\Pi} \approx 10^{-15}$ s/s to $\dot{\Pi} \approx 10^{-11}$ s/s as shown in Fig. 3.

As the situation now stands, the observational data for the white dwarfs are rather sparse: there is only *one* definite detection of a period change, namely the object PG 1159-035 (and this has a checkered history); there are no data currently available for DBVs; and there are only several upper limits for DAVs, the best of which is for the object G 117-B15A – $\dot{\Pi} \approx (1 \pm 3) \times 10^{-15}$ s/s.

The prototype of the DOV class (PG 1159) revealed a period change as far back as 1985: $\dot{\Pi} \approx -3 \times 10^{-11}$ s/s for the 516 s mode (Winget et al. 1985), and the result was “confirmed” in a subsequent WET run (XCOV3, Winget et al. 1991). This apparent period decrease was perplexing; exotic mode trapping effects had to be invoked to explain the phenomenon (Kawaler & Bradley 1994). However, more recent data, including another WET run (XCOV9), saw the measured period “decrease” transform into a more understandable period increase (Kepler 1997, Costa et al. 1998). This value is plotted in Fig. 3. This turnaround provides some cause for reflection: the earlier period decreases were obtained by identifying a quadratic term in the time of maximum of a sinusoidal fit to a particular pulsation mode, whereas the recent determination derives from measuring an actual increase in the period of the pulsation mode over the various data sets. It is worthwhile noting that this last measured $\dot{\Pi}$ shows that theory and observation have not yet adequately converged as they are about an order of magnitude different.

The “measured” $\dot{\Pi}$ for the DAV object G 117-B15A, has a not dissimilar history of change. Kepler et al. (1991) used an extensive photometric data base (including the WET run XCOV4) to infer a period increase of $\dot{\Pi} \approx 12 \times 10^{-15}$ s/s for the dominant 215 s pulsation mode of this object, but the inclusion of more recent data has led to the increase being “downgraded” to the limit given above (Kepler et al. 1995). The story is more succinctly conveyed via pictures: compare the first figures of Kepler et al. (1991) and (1995).

The measurement of period changes in the pulsating white dwarfs is of considerable interest. These data will yield information

about the white dwarf core composition, which in turn is important in estimating their ages. Correctly aged white dwarfs are in demand as galactic chronometers, and therefore, indirectly, they can shed independent light on the age of the Universe (Winget et al. 1987, Wood 1992).

4. PERIOD CHANGES IN L 19-2

Given the high degree of stability of the cool white dwarf pulsation modes, detecting any small period change is a challenging observational task: a large photometric data set with an extended observational time base is required. L 19-2 is a promising candidate for such a task. O'Donoghue and Warner (1987) used a single-site data set, spanning nearly 10 years, and obtained a limit of $\dot{P} < 3 \times 10^{-14}$ s/s on the period change of the principal 192.6 s pulsation mode. This limit is shown in Fig. 3.

The L 19-2 pulsation spectrum is not quite as simple as it first appears – even the amplitude DFT of the superior multi-site WET data masks frequency information (refer to Fig. 1). The additional data can be extracted by a prewhitening analysis, whereby the effective domination in the frequency domain of a large amplitude sinusoidal component can be essentially removed, by subtracting in the time domain a representation of its effect obtained by least squares fitting a sine curve to the temporal data. The residuals are then transformed into the frequency domain by calculating an amplitude DFT.

Prewhitening the WET data by the principal 192.6 s pulsation reveals the distinct presence of two satellite frequencies separated from the principal frequency by about 13 μ Hz. The deduced frequency multiplet is illustrated schematically in Fig. 4, and the values were obtained from an analysis of the preliminary WET data. This result confirms the O'Donoghue and Warner result, including the small ($\sim 1\%$) difference in splitting, all of which they extracted with some difficulty from their single-site data. The origin of this frequency split is presumed to be the slow rotation (~ 1 day) of the white dwarf, which separates in frequency an otherwise degenerate group of pulsations. The derived amplitudes of these satellite pulsations look sufficiently large that one might fairly ask why they are not directly evident in the amplitude DFTs – at least for the superior WET data. It appears that the near overlap of the one cycle per day

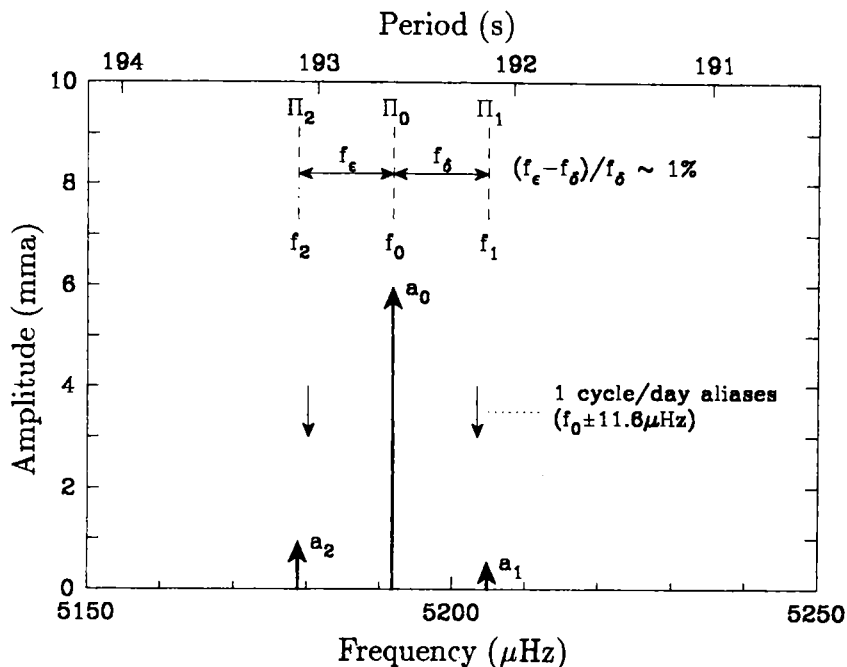


Fig. 4. A schematic representation of the fine structure split around the principal pulsation mode of L 19-2, as revealed by a pre-whitening analysis of the XCOV12 preliminary light curve. Note that both the higher (f_1) and lower (f_2) frequency pulsation modes are separated from the principal mode (f_0) by frequency differences f_δ and f_ϵ that themselves only differ by about 1%.

aliases ($\pm 11.6 \mu\text{Hz}$) that arise from the inevitable daily gaps in the photometric data (even for the WET) masks their presence.

These additional pulsations in the vicinity of the principal mode complicate the use of the standard *O-C* method of searching for very small period changes in a pulsation mode. In this method, one fits a sine wave to short (nightly) photometric data sets. The frequency of the sine curve is fixed and equal to the measured frequency of the principal mode, but the amplitude and phase are allowed to vary. A mismatch between the fitting frequency and the actual (constant) frequency in the data will lead to a linear change (with time) in the fitted zero phase over the observation set. However, a slow change in the physical period will first reveal itself as a quadratic term in this zero phase versus time plot. The zero phase is most conveniently represented in terms of the time difference between a fitted maxi-

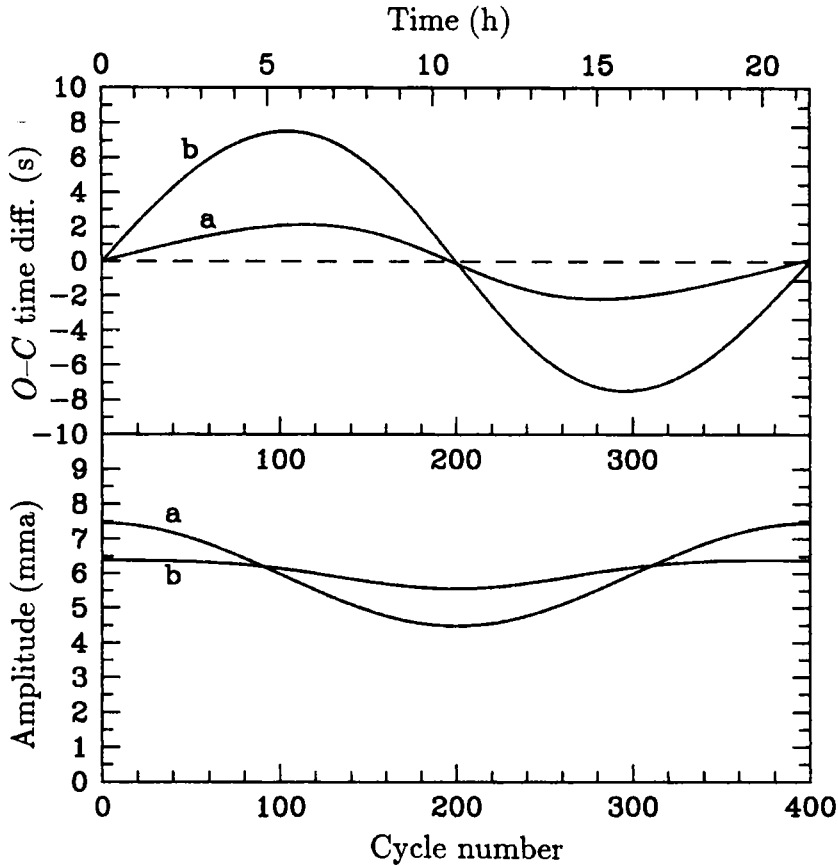


Fig. 5. The expected variation in amplitude and phase of a sinusoidal oscillation of constant frequency f_0 (~ 192.6 s) that matches the actual behavior of the frequency triplet depicted in Fig. 4. The effective amplitude is given in mma units, while the phase information is given in seconds in the *O-C* form. The two sets of plots marked *a* and *b* correspond to the range of variation arising from a 100-day cyclical change associated with the small difference between f_δ and f_ϵ (see Fig. 4).

mum and the corresponding time of maximum for a sinusoid with a fixed phase (hence the Observed – Calculated label). The very small possible period changes predicted for the cool white dwarfs should preclude any problems associated with uncertain cycle counts.

Fig. 5 depicts the impact the satellite frequency components will have on use of this method for the 192.6 s pulsation mode of L 19-2. There are two major effects that lead to a non-random variation of

the $O-C$ values. First, both the fitted amplitude and phase will vary cyclically with a period of approximately 20 hours, as illustrated in the graphs. This arises from the simple beating between the principal frequency, f_0 , and the two satellite frequencies f_1 and f_2 , which are both almost equally displaced from f_0 .

Second, the amplitudes associated with this 20 hour primary beating will vary over a much longer time scale. This arises from the fact that the frequency differences, f_δ and f_ϵ are *not* exactly equal, and the difference between these values leads to a second order beating effect, which impacts primarily on the amplitudes of the first order beating. This is illustrated in Fig. 5 by the two sets of curves a and b . In terms of the expected 20 hour cyclical $O-C$ phase variation, the amplitude of this effect will vary from about 2 s to 7 s over an approximately 100-day period (which corresponds to the $f_\epsilon - f_\delta \approx 0.12 \mu\text{Hz}$ second order beat period).

The values plotted in Fig. 5 were obtained by "brute force" (numerically) from the following model functions and the frequency and amplitude values depicted in Fig. 4:

$$I_O(t) = a_0 \cos \omega_0 t + a_1 \cos(\omega_1 t + \phi_1) + a_2 \cos(\omega_2 t + \phi_2),$$

$$I_C(t) = a_0 \cos \omega_0 t$$

where $\omega_0 = 2\pi f_0$, etc.

The plotted amplitude values simply correspond to the maximum values of the function $I_O(t)$, and the $O-C$ values correspond to the time difference between corresponding maxima of $I_O(t)$ and $I_C(t)$. The values were calculated over the primary beat period of 400 cycles of the function $I_O(t)$, while the two set of curves correspond to choices of $\phi_1 = \phi_2 = 0$ (a) and $\phi_1 = \pi$, $\phi_2 = 0$ (b). The fact that $\omega_\delta = \omega_1 - \omega_0$ and $\omega_\epsilon = \omega_0 - \omega_2$ are *not* identical means that the 20 hour beat pattern cycles between the a and b extremes, and the fact that they are *nearly* equal means that this takes a long time.

The origin of the beat amplitude extremes of the maximum values of $I_O(t)$ readily follows from a consideration of the relative phases of the three arguments ω_0 , $\omega_1 t + \phi_1$ and $\omega_2 t + \phi_2$ of the cosines, but the amplitude of the $O-C$ phase beating is more difficult to discern. An analytical expression for this quantity can be derived by writing $I_O(t)$ in the form

$$I_O(t) = A(t) \cos(\omega_0 t + \phi(t))$$

and obtaining an expression for $\phi(t)$ by expanding the cosines and matching terms. This procedure yields

$$\tan \phi(t) = \frac{a_1 \sin \omega_\delta t - a_2 \sin \omega_\epsilon t}{a_0 + a_1 \cos \omega_\delta t + a_2 \cos \omega_\epsilon t},$$

where the relative phases ϕ_1 and ϕ_2 have been set to zero since they are of secondary importance for the case here ($\omega_\delta \neq \omega_\epsilon$).

If we write $\omega_\epsilon = \omega_\delta + \Delta\omega$ then the expression for $\phi(t)$ can be written in the form

$$\tan \phi(t) = A_\phi(t) \cos(\omega_\delta t + \theta_\phi(t)),$$

where $A_\phi(t)$ is given by

$$A_\phi(t) = \frac{[r_1^2 + r_2^2 - 2r_1 r_2 \cos \Delta\omega t]^{1/2}}{1 + [r_1^2 + r_2^2 + 2r_1 r_2 \cos \Delta\omega t]^{1/2} \cos(\omega_\delta t + \theta_d(t))}$$

with $r_1 = a_1/a_0 \approx 0.09$ and $r_2 = a_2/a_0 \approx 0.16$.

The phase factors, $\theta_\phi(t)$ and $\theta_d(t)$ above, are themselves cyclical functions of time via the functions $\sin \Delta\omega t$ and $\cos \Delta\omega t$, but it follows from the above expressions that the time-dependence of the phase $\phi(t)$ will be dominated by two effects: it will vary periodically with the primary beat angular frequency $\omega_\delta \approx \omega_\epsilon$, and the amplitude of this beat will vary cyclically between a minimum and maximum value with a time scale determined by the angular frequency difference $\Delta\omega = \omega_\epsilon - \omega_\delta$. Substituting the appropriate values in the above expressions yields the 2 s to 7 s amplitude variation illustrated in Fig. 5.

This nonrandom variation of the $O-C$ phase will undoubtedly limit the attainable precision for the principal pulsation mode of L 19-2. However, given that a typical observing run is a significant fraction of the principal beat frequency of ~ 20 hours, averaging over a number of runs in an observing season should significantly reduce the effect of this variation. So, it is not as bad as it seems.

5. THE CURRENT POSITION AND DISCUSSION

The previous high-speed photometric data set on L 19-2 (1976–1985) has been supplemented by data obtained recently (1994–1997). A significant contribution is the WET data obtained in 1995. The potential of the current data set is illustrated in Fig. 6 by plotting

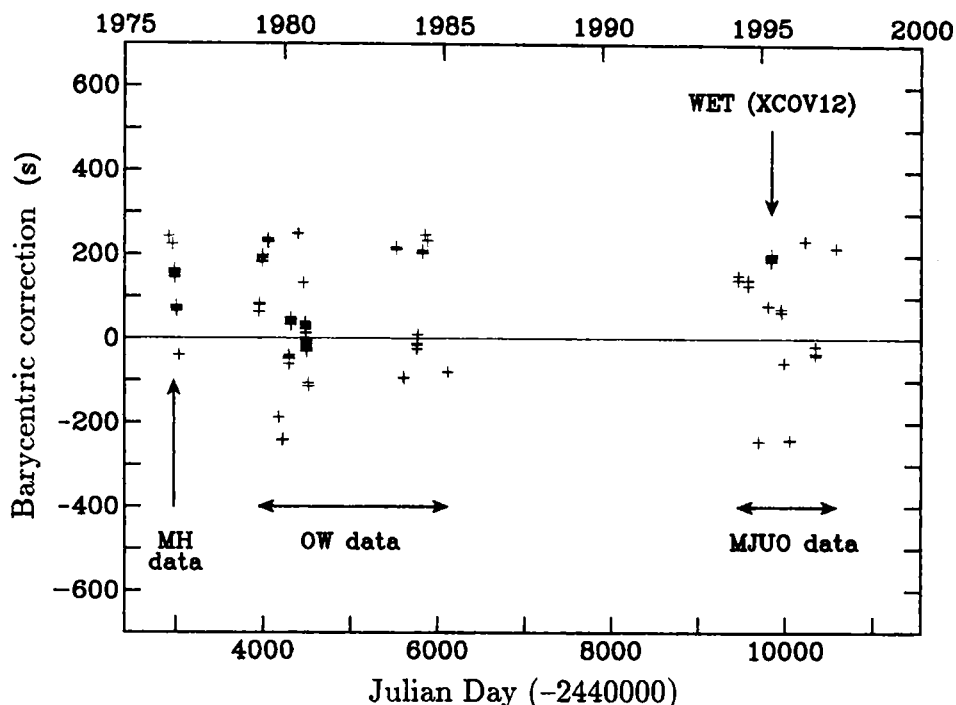


Fig. 6. The barycentric time corrections for all available photometric runs on L 19-2 plotted versus date of observation to illustrate the 20 year time base of the date set. The MH points correspond to the early McGraw (1977) and Hesser et al. (1977) observations, while the OW points represent the extensive single-site data of O'Donoghue and Warner (1982, 1987) and the more recent data consists of the 1995 WET run (XCOV12) and supporting observations from Mt. John (MJUO).

the required barycentric time corrections for all the available photometric runs ranging from the 1976 discovery data (McGraw 1977) to the latest Mt. John 1997 data.

Even though the new multi-site data obtained on this object has confirmed its status as a low-amplitude, few-mode DAV pulsator, and therefore ensured its interior properties will not yield easily to an asteroseismological probe, a new more definitive pulsation spectrum will enable progress to be made along the lines of Bradley (1996). In addition, the new extended 20 year time base of the data set may even produce a definite measured period change for a DAV white dwarf. At the very least, it will enable the upper limit to be extended so as to compete with the other interesting object, G 117-B15A.

Although there is some uncertainty about the model-dependent conclusions, spectroscopic observations of the DAVs (Bergeron et al. 1995) suggest that L 19-2 has a higher T_{eff} and is more massive than G 117-B15A. The higher effective temperature should lead to a larger $\ddot{I}$. However, appropriate models (Bradley & Winget 1991) predict that, other things being equal, L 19-2 will possess a smaller $\ddot{I}$. This is in agreement with the simple physical argument that a more massive white dwarf has a larger heat capacity *and* a smaller surface area. Both of these factors contribute to a slower loss of internal energy, and, therefore, a smaller $\ddot{I}$. It may be that the period decrease for L 19-2 will be more difficult to observe than for G 117-B15A, if there are no other factors at work such as an enhanced $\ddot{I}$ for the particular mode observed.

In conclusion, it is interesting to note that the absence of $\ddot{I}$ observational data for DBV stars may soon be rectified. The new low amplitude DBV object (EC 20058-5234) discovered as part of the Edinburgh-Cape faint blue object survey (Koen et al. 1995) has a *relatively* simple observed pulsation spectrum. This object is a good candidate for a period stability analysis. A recent southern hemisphere WET run on this object (XCOV15 in 1997) confirmed that a significant amplitude pulsation near 256 s is free from fine structure, and can be fully resolved in a nightly observation from a single site. Given that the anticipated $\ddot{I}$ values for DBVs are a factor of 10 larger than for DAVs, the 1994 discovery data on EC 20058 when combined with the new WET data and future single-site data, may yield an observational determination within a few years.

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REFERENCES

- Bergeron P. et al. 1995, ApJ, 449, 258
Bradley P. A. 1996, ApJ, 468, 350
Bradley P. A. 1998, ApJ (in press)
Bradley P. A., Winget D. E. 1991, ApJS, 75, 463
Bradley P. A., Winget D. E., Wood M. A. 1992, ApJ, 391, L33
Bradley P. A., Winget D. E., Wood M. A. 1993, ApJ, 406, 661
Brassard P. et al. 1992, ApJS, 81, 747
Brown T. M., Gilliland R. L. 1994, ARA&A, 32, 37
Clemens J. C. 1995, Baltic Astronomy, 4, 142
Costa J. E. S., Kepler S. O., Winget D. E. 1998, ApJ (in preparation)
Hesser J. E., Lasker B. M., Neupert H. E. 1977, ApJ, 215, L75
Kawaler S. D., Bradley P. A. 1994, ApJ, 427, 415
Kawaler S. D., Hansen C. J., Winget D. E. 1985, ApJ, 295, 547
Kawaler S. D., Winget D. E., Hansen C. J. 1985, ApJ, 298, 752
Kawaler S. D., Winget D. E., Iben I., Hansen C. J. 1986, ApJ, 302, 530
Kepler S. O. 1997, private communication
Kepler S. O. et al. 1991, ApJ, 378, L45
Kepler S. O. et al. 1995, Baltic Astronomy, 4, 221
Koen C. et al. 1995, MNRAS, 277, 913
McGraw J. T. 1977, ApJ, 214, L123
Nather R. E., Winget D. E., Clemens J. C., Hansen C. J., Hine B. P. 1990, ApJ, 361, 309
O'Donoghue D., Warner B. 1982, MNRAS, 200, 573
O'Donoghue D., Warner B. 1987, MNRAS, 228, 949
O'Donoghue D. et al. 1998 (in preparation)
Sullivan D. J. 1995, Baltic Astronomy, 4, 261
Taylor J. H., Stinebring D. R. 1986, ARA&A, 24, 285
Winget D. E. et al. 1985, ApJ, 292, 606
Winget D. E. et al. 1987, ApJ, 315, L77
Winget D. E. et al. 1991, ApJ, 378, 326
Winget D. E. et al. 1994, ApJ, 430, 839
Wood M. A. 1992, ApJ, 386, 539

